

BOUNDARY LAYER CONTROL OF HYPERSONIC AIR INLETS

D. A. Ogorodnikov, V. T. Grin and N. N. Zakharov

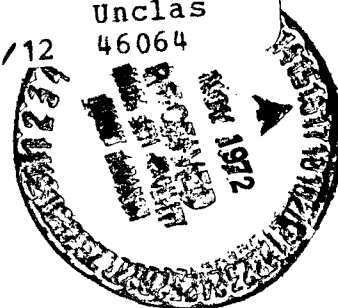
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BOUNDARY LAYER CONTROL OF HYPERSONIC AIR INLETS

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Cover Page Title

ABSTRACT. The article contains a discussion of boundary layer control with respect to present methods of hypersonic air inlet boundary layer control using injection. Formuli, pictures and graphs accompany the article.

An increase in the Mach number of aircraft with air-breathing jet engines /1* leads to a significant deterioration of the characteristics of air inlets which are used in them. The basic reason for a deterioration of the characteristics is an increase in the effect of air viscosity. Notwithstanding the fact that braking of a flow in the hypersonic air inlet designed for engines with supersonic fuel combustion is accomplished up to $M > 1$, increase of pressure in it reaches $\bar{P} = 100$ and greater. In theory, such an increase in pressure can be obtained in a system of weak shock waves with a comparatively low level of total pressure loss. However, realization of such braking of the flow encounters the development of a separation of the boundary layer which causes a sharp increase in losses, related to a vortex formation and in a number of cases does not permit the organization of a calculated flow pattern. Specifically, for example, the hypersonic air inlet fails to start at a calculated value of the throat area due to separated regions which develop at the intake. Therefore, to prevent separation of the boundary layer it is necessary that the boundary layer control systems be organized.

At comparatively low hypersonic velocities, boundary layer control is accomplished by means of suction or overflow. Using such a method one can successfully increase the magnitude of the coefficient of total pressure σ ,

*Numbers in the margin indicate pagination in the foreign text.

decrease the irregularity of the velocity field, and extend the stable operating range of the air inlet with a slight consumption of the air being drawn in, comprising 1-3% of the total flow through the air inlet.

The theoretical flow analysis conducted with a number of simplifying assumptions, with respect to the boundary layer in the region of its interaction with the shock wave with suction or overflow of the boundary layer, as well as comprehensive experimental investigations have demonstrated that as the result of suction or overflow of the portion of the boundary layer next to the wall, an increase occurs in the fullness of the velocity profile in the boundary layer, and, as a result, an increase of the so-called critical pressure ratio \bar{P}_{cr} , i.e., a ratio of pressure in the shock wave at which the flow in the boundary layer can be maintained continuously. In such a manner, air inlets are successfully designed with a continuous flow in a large part of the air passage. However, upon transition to hypersonic flight speeds, M numbers on the surface of the intake central body become quite great, $M \geq 3$. As a result of this, for deflection of the boundary layer it is necessary to have apertures of rather large size which leads to design difficulties. If one organizes overflow of the boundary layer through slotted air passages, the extent of the effective work of such passages is limited by lengths of an order of 10 thicknesses of the boundary layer to the rear of the point of overflow. Therefore, for multiregime air inlets, where the incidence points of the shock waves and the boundary layer move with a change in flight regime, such a control method becomes ineffective or requires the organization of several overflow air passages which, in addition to design difficulties, leads to an increase in the consumption of intake air. Nevertheless, this method is well recommended for supersonic velocities, and, taking into account a certain inertia in design solutions, will apparently be used at hypersonic velocities as well. However, in addition to the indicated method of controlling the boundary layer, other extremely effective means can also be used which increase the stability of the boundary layer with respect to separation. Here, the natural characteristics of hypersonic power plants are used. These means of boundary layer control are a tangential injection of gas into the boundary layer and cooling of the fairings, i.e., a decrease of the temperature factor $\bar{T}_w = T_w/T_0$, or the joint

action of both methods. T_w is the surface temperature; T_0 is braking temperature.

Just as with suction or overflow of the boundary layer, tangential injection or cooling leads to an increase of the momentum of the portion of the boundary layer near the wall and in this way increases the magnitude of the critical ratio of pressures. Knowledge of the dependence of the magnitude of \bar{P}_{cr} on the parameters which determine the characteristics of the injected jet, and on the temperature factor \bar{T}_w allow one to design the intake central body of the hypersonic air inlets with a continuous flow in the boundary layer. It should be noted that for tangential gas injection into the boundary layer one can use a system of gasified fuel feed. For determining the required ratios, computational and experimental investigations were conducted, in the general form, of the effect of heat-dissipation and tangential injection on the magnitude of the critical ratio of pressures and the data obtained were used for organizing continuous flow in hypersonic air inlets.

The flow which forms during tangential injection into the boundary layer can be approximately divided into three regions (Figure 1).

1. The external, "unperturbed" region in which the velocity profile maintains its former shape.

2. The region in which the injected jet mixes with the boundary layer; in this region the velocity profile is described by the law for a jet flow.

3. A thin, region near the wall, which is a new boundary layer, formed as the result of flow of the injected jet around the surface. The velocity profile in this boundary layer changes dependent upon the distance from the point of injection, but as experimental investigations demonstrate, it is well described by an exponential function

$$\frac{u}{u_0} = \left(\frac{y}{\delta} \right)^{1/n}, \quad u'_{n0} -$$

velocities in the boundary layer in the unperturbed flow, δ - the thickness of the boundary layer. In connection with the thinness of this boundary layer near the point of injection and for satisfying the computational and experimental data one can assume value $n = 9$.

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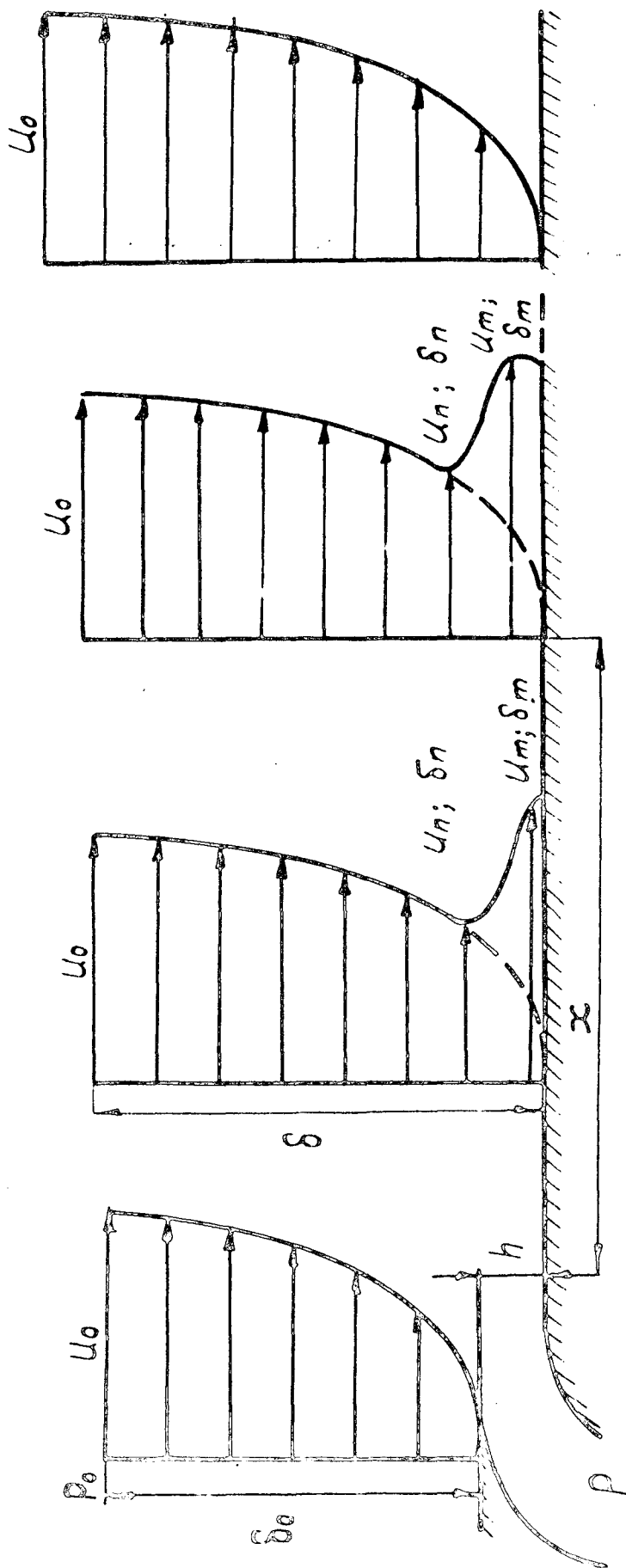


Figure 1.

Introducing a number of assumptions, one can describe the velocity profile during tangential injection. The equation of continuity will have the form:

$$\left(\int_0^{\delta} \rho u_{fi} \right) + G_{in} + \Delta G = \left(\int_0^{\delta} \rho u_{fi} \right)_{X=X_S} \quad (1)$$

Here G_{in} is flow of air taken in and ΔG is the flow rate passing through the outer limit of the boundary layer at a distance from the injection site $X = X_0$ to the cross-section in question, $X = X_S$. The flow rate through the outer limit of the boundary layer during injection and without it is assumed to be the same.

It is also assumed that a change in the boundary of the "perturbed" region (point "N" on the velocity profile) occurs due to ejection of the injected jet of the throughput from the accompanying boundary layer. The ejection characteristics of the injected jet are well described by the formula:

$$\int_0^{\delta_n} \rho u_{fi} = G \gamma \sqrt{x/n} \quad (2)$$

where $\gamma = 0.26$ empirical coefficient. The form of the velocity profile in the mixing region can be given in the form:

$$\frac{u - u_n}{u_m - u_n} = \left(1 - \eta^{3/2} \right)^2, \quad \text{where} \quad \eta = \frac{y - \delta_m}{\delta_n - \delta_m}$$

Calculation of change in the local coefficient of friction allows one to measure the increase in the stability of the boundary layer to separation during tangential injection. Using an hypothesis of the automodeling of change in the characteristics of the boundary layer before the point of separation, one can obtain the relationship of:

$$C_{p \text{ cr}} = \frac{P_{\text{cr}} = P_{\infty}}{1/2 \rho_{\infty} u_{\infty}^2}$$

to the local coefficient of friction: $C_{p \text{ cr.in}} / C_{p \text{ cr}} = \sqrt{\frac{C_{f \text{ in}}}{C_{f \infty}}}$

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Here C_{pcr} and C_{pcrin} are the coefficients of critical pressure at which separation occurs of the conventional boundary layer and the boundary layer during injection respectively (the subscript pertains to parameters of the unperturbed stream ahead of the interaction region). In Figure 2 a change in the critical ratio of pressures is given $\bar{P}_{cr} = P_{pcrin}/P_{pcr}$ with injection as a function of $\bar{X} = X/h$ with two values of the relative flow of injected air $\bar{G} = G_{in}/G_0 = 0.05$ and 0.1 . Here, in fact, the experimental points are drawn for $\bar{G} = G_{on}/G_0 = 0.04$ and 0.006 . It is apparent that, the approximate character of the discussion notwithstanding, the coincidence of the calculated and experimental data is satisfactory.

For a calculated analysis of the effect of heat dissipation of separation of the boundary layer, the relationship of the friction coefficient to the determining parameters is written in the general form

$$\frac{\tau_w}{\rho_0 u_0^2} = \varphi \left(M_0, \bar{T}_w, \frac{dP_0}{dx}, \frac{Z}{\rho_0 u_0^2}, \frac{\rho_0 u_0 Z}{M_0} \right) \quad (3)$$

It is known that the proximity of a turbulent boundary layer to separation is,

for an adiabatic wall, determined by the parameter $\xi = \frac{dP_0}{dx} \frac{Z}{\rho_0 u_0^2}$ where

dP_0/dx is the pressure gradient in the external flow, Z is the characteristic size of the boundary layer. At the point of separation the parameter ξ achieves the critical value ξ_{cr} . Solving the equation (3) at the point of

separation relative to $\frac{dP_0}{dx} \frac{Z}{\rho_0 u_0^2}$ and expansion of the obtained expression in a series according to the parameter $\frac{\mu}{\rho_0 u_0 Z}$ one obtains

within at the limits with $\mu \rightarrow 0$.

$$\frac{dP_0}{dx} \frac{Z}{\rho_0 u_0^2} = \varphi(M_0, \bar{T}_w).$$

In an incompressible fluid, the value of the function $\psi(0.1) \approx 0.015$, if one takes the thickness of the extension of the boundary layer δ^* as a characteristic value. /6

An approximate presentation of the frictional stress in the separation cross-section in the form of a polynomial of the 4th degree of $\bar{C} = C/\delta$, and for determining the coefficients, boundary conditions are used which devolve from the motion equations at the point of separation. As a result, the following is obtained at the cross-section of separation:

$$\frac{\tau}{\rho_0 u_0^2} = \frac{d\rho_0}{dx} \frac{\delta}{\rho_0 u_0^2} \left(\frac{\bar{y}}{c} - \frac{\bar{y}^4}{c} \right) \quad (4)$$

Disregarding molecular friction in the separation cross-section and presenting turbulent friction in the form suggested by Prandtl, one obtains:

$$\bar{\rho} \bar{\ell}^2 \left(\frac{\partial \bar{u}}{\partial \bar{y}_c} \right) = \frac{d\rho_0}{dx} \frac{\delta}{\rho_0 u_0^2} \left(\frac{\bar{y}}{c} - \frac{\bar{y}^4}{c} \right) \quad (5)$$

$$\bar{\rho} = \frac{\rho}{\rho_0}, \quad \bar{u} = \frac{u}{u_0}, \quad \bar{\ell} = \frac{\ell}{\delta}$$

integrating the differential equation (5) with assumption of preservation similarity of the velocity profile and of the overflow profile, one obtains:

$$\psi(M_0, \bar{T}_w) = \frac{d\rho_0}{dx} \frac{\delta^*}{\rho_0 u_0^2} = \frac{2}{\kappa-1} \frac{1}{M_0^2} \frac{\delta^*}{\delta} \left(\frac{\delta}{\delta^*} \right)_H (\alpha - \beta)^2 \psi(0.1) \quad (6)$$

where α and β are known functions of the number $M_0 = \bar{T}_w$.

With an unlimited increase in the number M_0 , the parameter of separation tends asymptotically toward zero. Cooling of the surface enables one to increase the stability of the boundary layer to separation. Physically, this is explained by an increase in the sensitivity of the boundary layer to the pressure gradient as the result of an increase in the gas density in the region near the wall.

The conditions of a flow separation developing during the interaction of a shock wave with a turbulent boundary layer will now be examined. For a flow of non-viscous gas whose boundary is determined by the thickness of displacement of the boundary layer, the linearized Prandtl-Meyer relationship is used.

$$\left| \frac{p - p_1}{\frac{1}{2} \rho_0 u_0^2} = \frac{1}{(M_0^2 - 1)^{1/2}} \frac{d\delta^*}{dx} \right| \quad (7)$$

and for a viscous gas in the vicinity of a point of separation, one uses condition (6). From a simultaneous examination of the conditions in a viscous and non-viscous gas, the following are obtained:

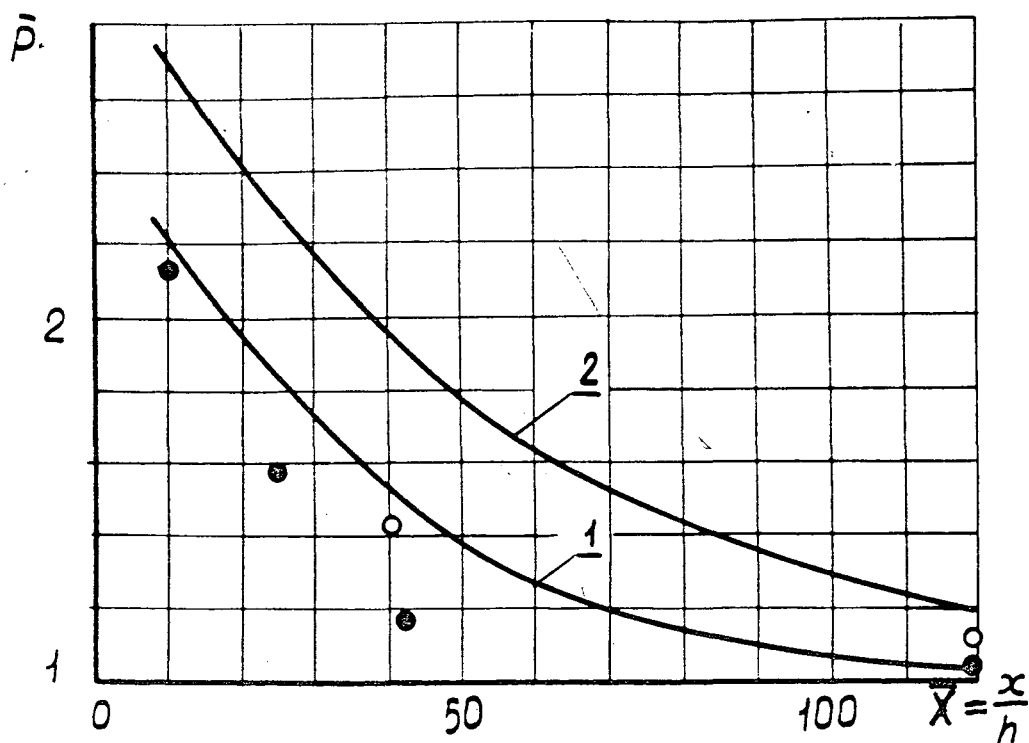
$$\bar{p}_{kp} = n \frac{\kappa M_0^2}{2} \left\{^{1/2} (M_0^2 - 1)^{-1/4} + 1 \right\} \quad (8)$$

The value of the coefficient of proportionality $n = 4.2$ is found from experiments on the interaction of a shock wave with a turbulent boundary layer on a thermally insulated surface. In Figure 3 the results are given for a calculation of the value:

$$C_{p_{kp}} = \frac{C_{p_{kp}}(\bar{T}_w)}{C_{p_{kp}}(1)} = \left[\frac{\sum_{kp}(\bar{T}_w)}{\sum_{kp}(1)} \right]^{1/2} \quad (9)$$

by the method introduced and the experimental data which were obtained in the various models. A good agreement of the results of the experiment and the calculations is obtained.

The stated means of control were used for improving the characteristics of hypersonic air inlets. The experimental models were simple, flat air inlets with a central inlet body in the form of a flat variable wedge with an angle of $\beta_w = 19^\circ$. The relative area of the throat was chosen equal to $\bar{F}_T = 0.25$. The investigation was conducted at a $M = 11.6$. In the course of the experiment a constant increase in friction pressure was maintained, and the Reynold's number at which air inlet starting occurred was determined. Here, the surface of the central inlet body was cooled, with the goal being to obtain various values of the temperature factor \bar{T}_w . In Figure 4, the dependence of the number Re_H , at which the air inlet starts, on \bar{T}_w is given. A significant



1 - $\bar{G} = 0.005$; 2 - $\bar{G} = 0.1$; • - $\bar{G} = 0.04$; o - $\bar{G} = 0.06$.

decrease in the number Re_H is apparent with respect to starting during cooling of the central inlet body. The process of decrease and disappearance of the separation region at the point of incidence on the central inlet body and the shock wave deflected from the shell is well illustrated in Figure 5 by the distribution of static pressure along the central inlet body. With a decrease in the temperature factor \bar{T}_w , the initial point of pressure increase is displaced to the break of the central inlet body. (Here the experimental data are introduced for an axisymmetrical model with $M = 6$; $\beta_w = 10^\circ$; $\bar{F} = 0.34$; $Re = 0.86 \times 10^6$. In this same figure, optical photographs of the flow are given. One can see a disappearance of the separation region in front of the intake of the air inlet with cooling of the central inlet body. The field of total pressures in the internal passage of the air inlet, introduced in this same figure, demonstrates that with cooling one observes a significant

increase of total pressure in the core of the flow. Similar results are also obtained when using a tangential injection in front of the region of incidence of the shock wave deflected from the shell. In Figure 6 the distribution of static pressure along the central inlet body is presented, as well as that along the shell; these data were obtained on a model of an axisymmetrical air inlet with $M = 6$; $\beta_w = 10^\circ$; $\bar{F}_T = 0.34$ and number $Re = 0.86 \times 10^6$. The optical photographs of flow are given here as well. Turning on the tangential injection causes a disappearance of the separation region in front of the intake of the air inlet ($\bar{G}_{in} = 3\%$).

Hence, the examined systems for controlling the boundary layer are an effective means for significantly improving the characteristics of hypersonic air inlets.

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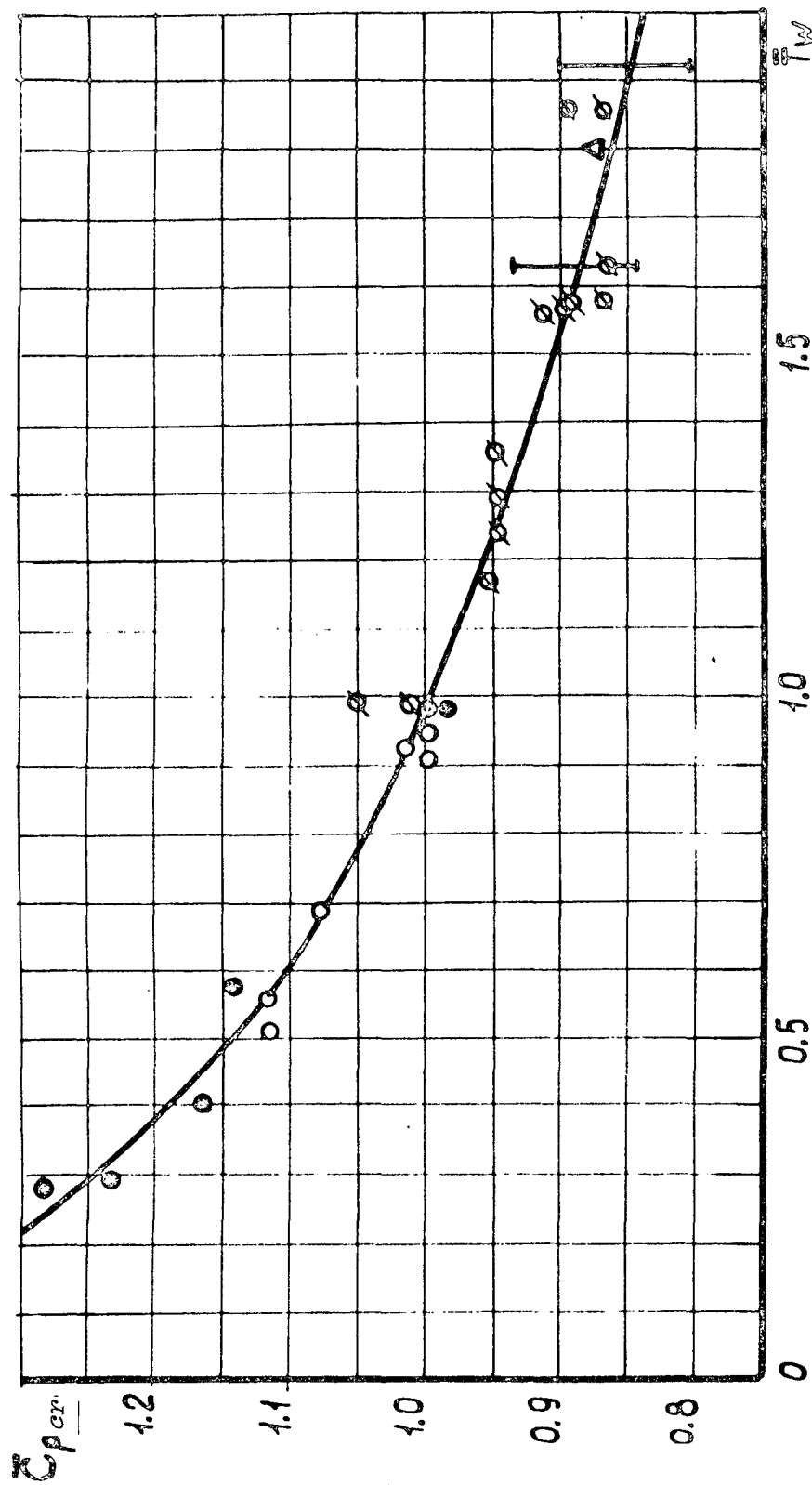


Figure 3.

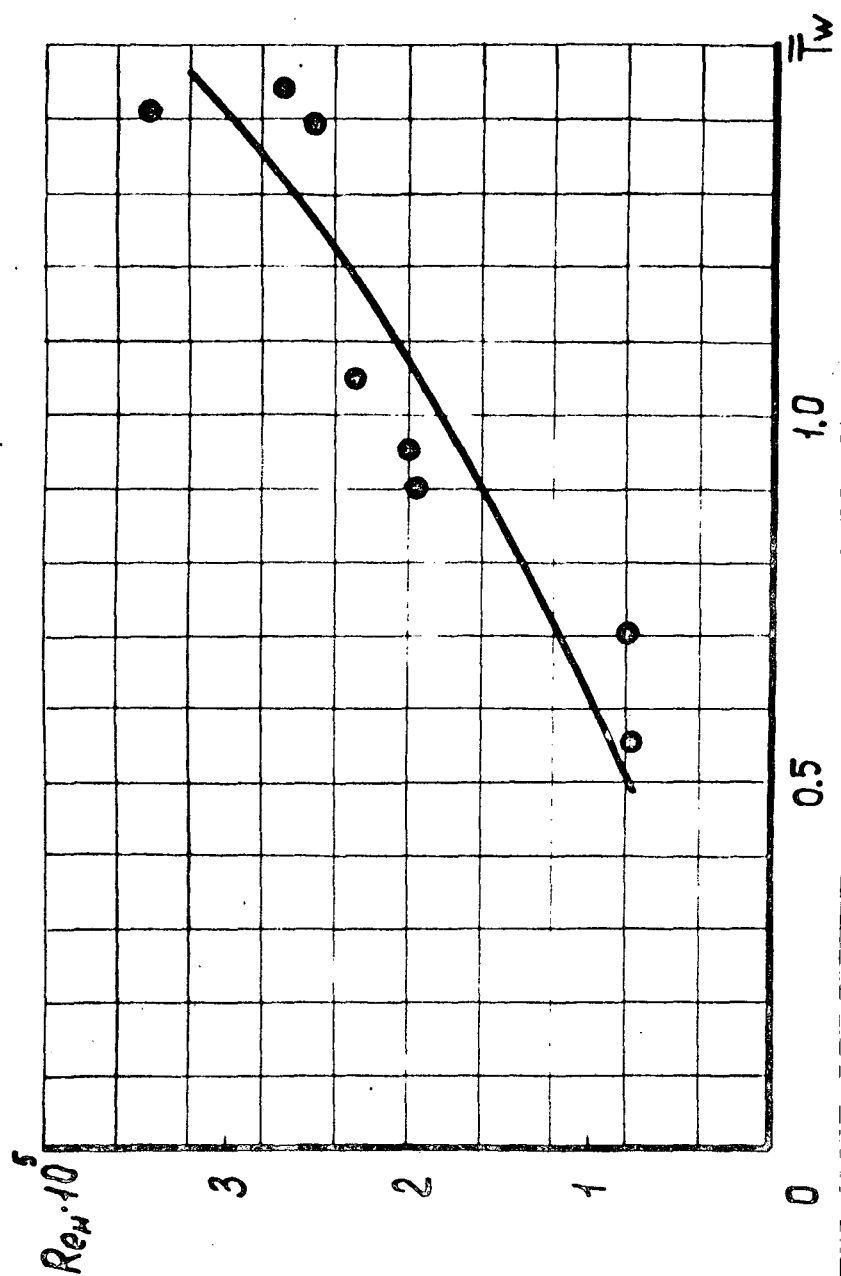


Figure 4.

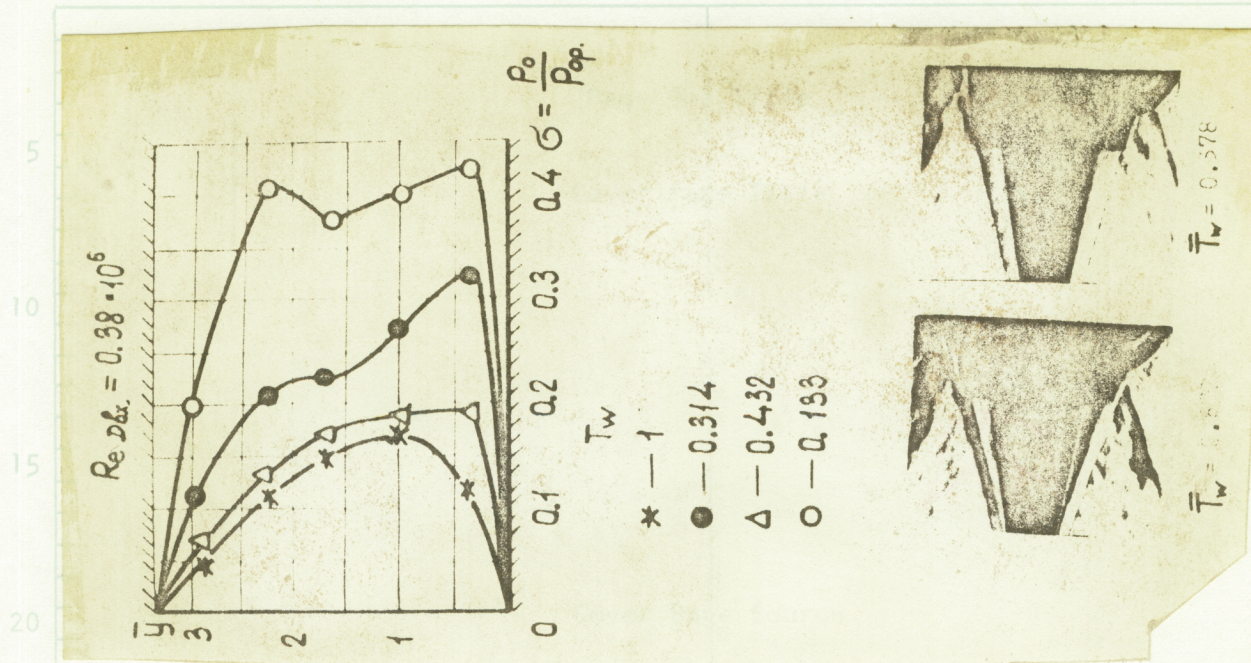
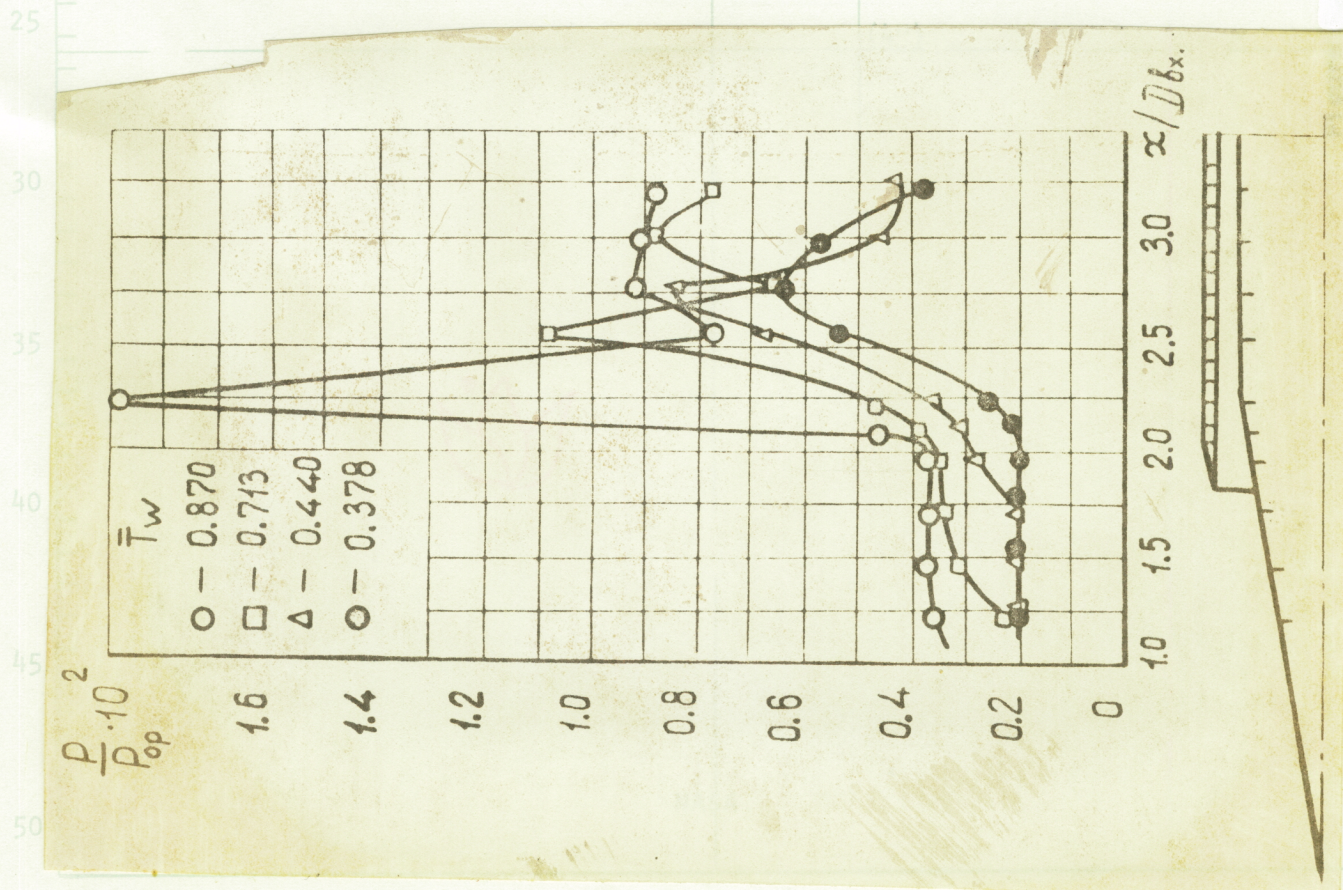


Figure 5.

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15
20
25
30
35
40
45
50

$$Re_{\delta x} = 0.38 \cdot 10^6$$

$$\Delta \psi = \frac{G \delta x}{G}$$

- — 0
- — 0.02
- — 0.03
- △ — 0.13

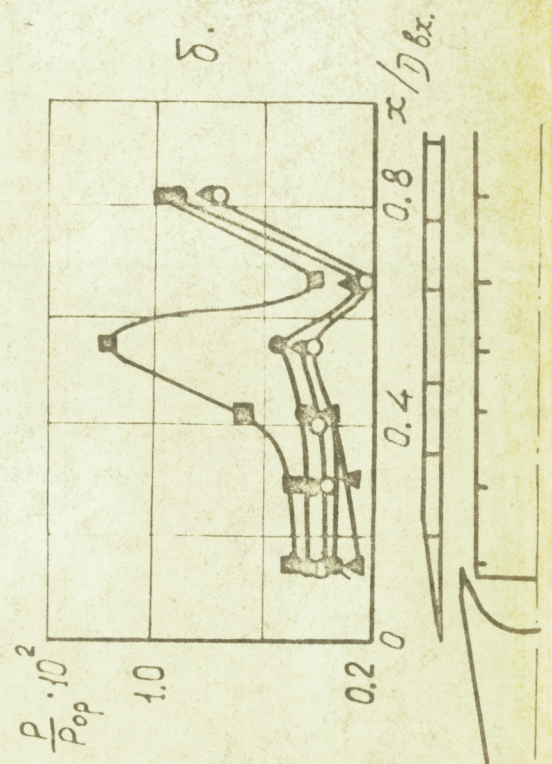
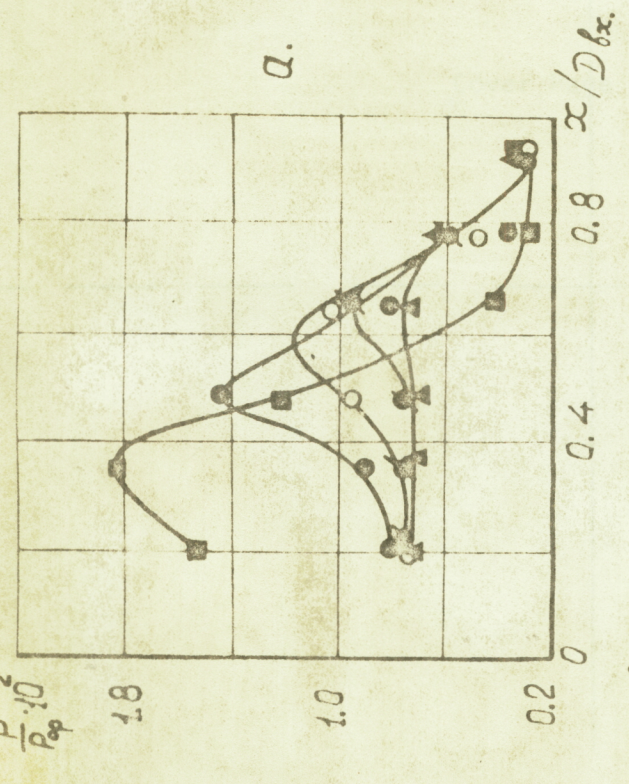


Figure 6.